Rare species of dark matter

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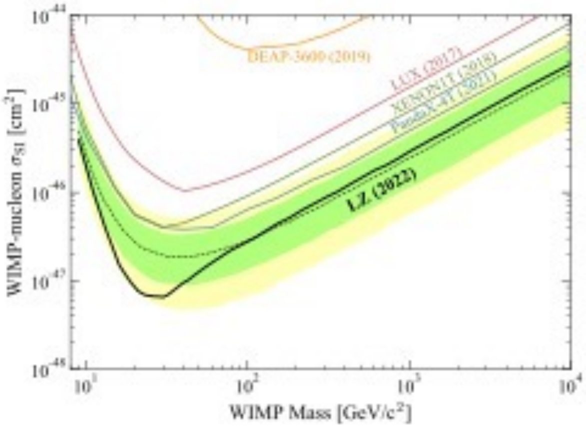
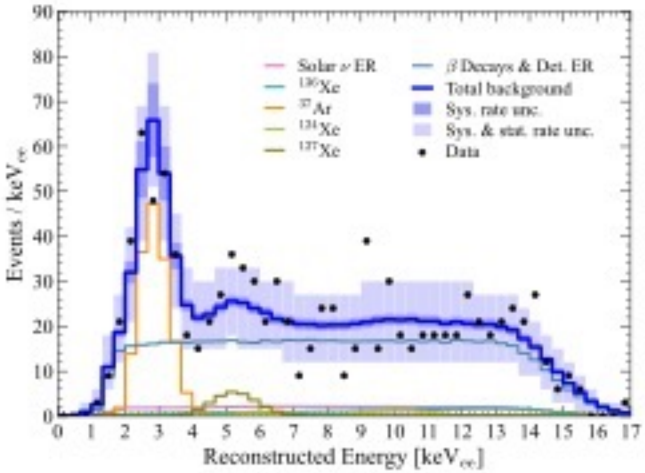
- Introduction. Difficult spots for direct detection. A. Light dark matter. B. Thermalized dark matter fraction. *Dark matter through multiple collisions.*
- Light dark matter reflected from A. the Sun, B. from cosmic rays. Constraints on scattering cross section.
- Rare species of strongly interacting dark matter. DM flux: “traffic jam” and hydrostatic population
- Signatures: A. Signatures for neutrino detectors: Direct annihilation inside underground neutrino detectors. B. Possible use of underground accelerators: a scheme to search for strongly interacting DM in double collision C. Constraints from the DM detectors at nuclear reactors. D. De-excitations of nuclear isomers. Interesting case of ^{180}Ta.

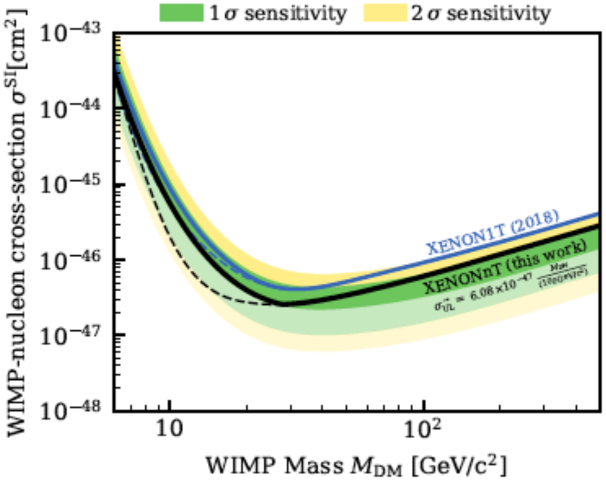
References and Collaborators

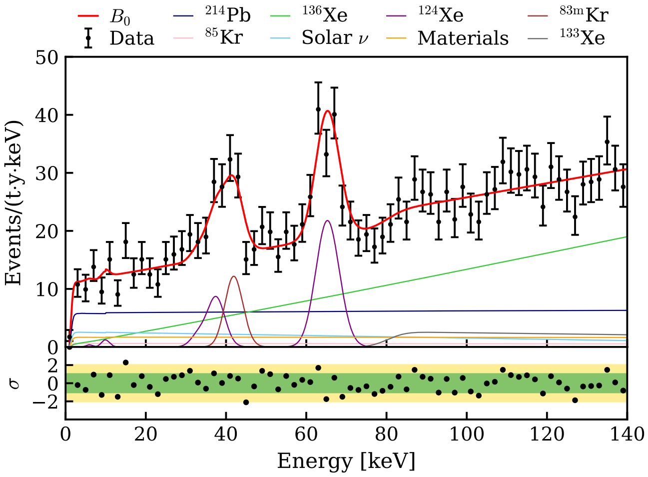
- New sensitivity to light dark matter via solar reflection (With H. Nie, H. An, J. Pradler, A. Ritz). (2018 PRL, 2021 PRD)
- Acceleration of DM by cosmic rays (With T. Bringmann). 1810.10543 [hep-ph], (2019 PRL)
- Possible use of underground accelerators? (With M. Moore, D. McKeen, D. Morrissey, H. Ramani). 2202.08840[hep-ph]
- Constraints on Dark Matter from Nuclear Reactors. 2402.03431 [hep-ph] (With Y. Ema, A. Ray)
- Constraints on Dark Matter from Nuclear Isomers. 1907.00011 [hep-ph] (With S. Rajendran, H. Ramani). B. Lehnert et al., 1911.07965 [Astro-ph.co], PRL 2020
- I also worked on related topics with A. Berlin, H. Liu.

- Impressive 2022-24 updates of Direct detection limits by LZ, XenonNT.









Blind areas for direct detection

1. ~MeV scale dark matter: Kin Energy $= mv^2/2 \sim (10^{-3}c)^2(\mathrm{MeV}/c^2) \sim \mathrm{eV}$.
   Below the ionization threshold! ($v < 2*10^{-3}$ c)

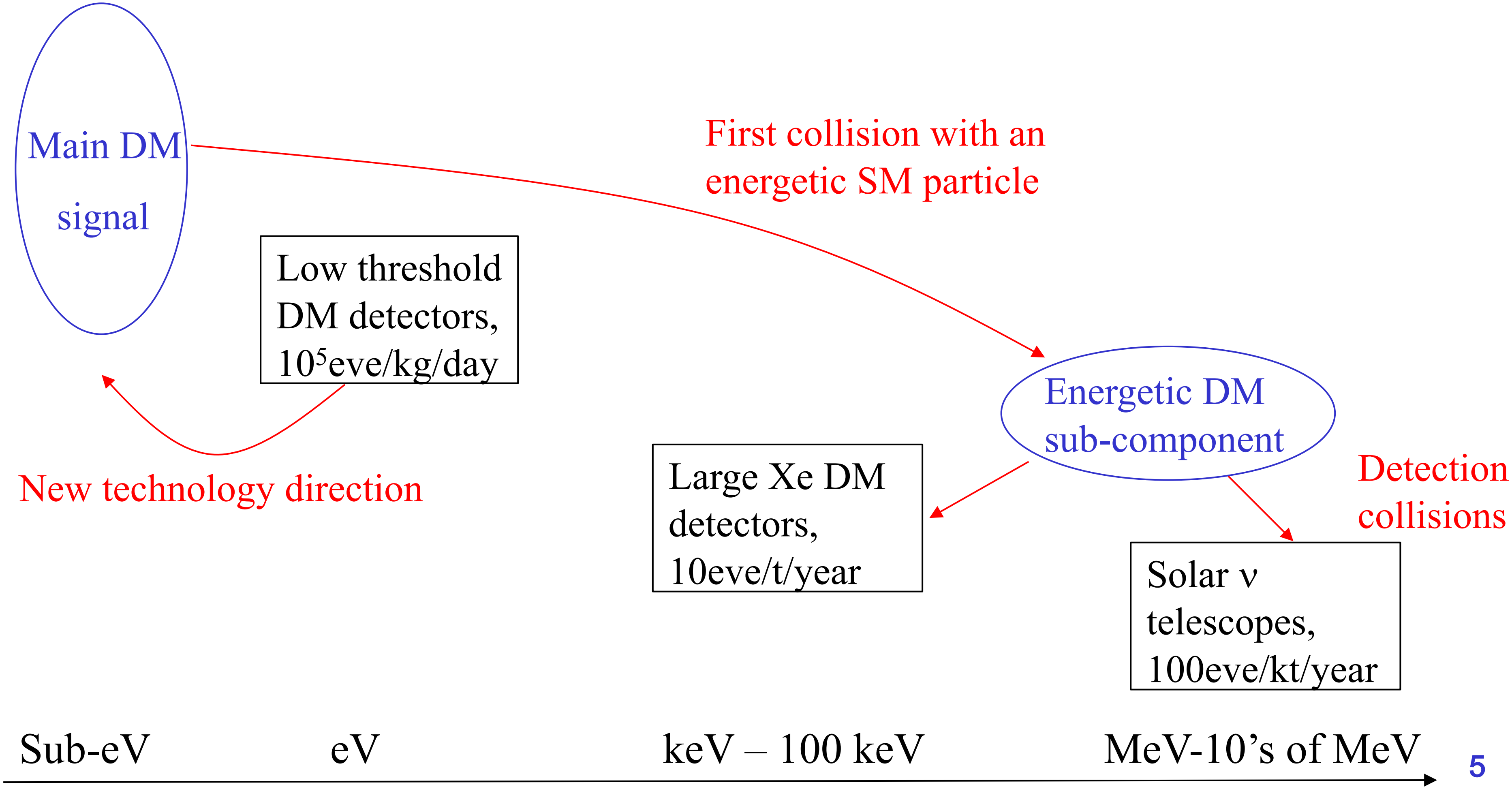
2. Strongly-interacting subdominant component of Dark Matter. Thermalizes before reaching the underground lab,
   Kin energy ~ kT ~0.03 eV

   (Typically cannot be entire DM, but is limited to fraction $f_\chi < 10^{-3}$)

   Below the ionization threshold!

Different strategies to cover blind spots

1. Develop new technologies that will be sensitive to the sub-eV energy deposition.
2. Explore multiple collisions of DM to fill in “blind spots”



Main DM signal

First collision with an energetic SM particle

Low threshold DM detectors, 10^5eve/kg/day

Energetic DM sub-component

New technology direction

Large Xe DM detectors, 10eve/t/year

Detection collisions

Solar ν telescopes, 100eve/kt/year

Sub-eV

eV

keV – 100 keV

MeV-10’s of MeV

Excess background at low energy

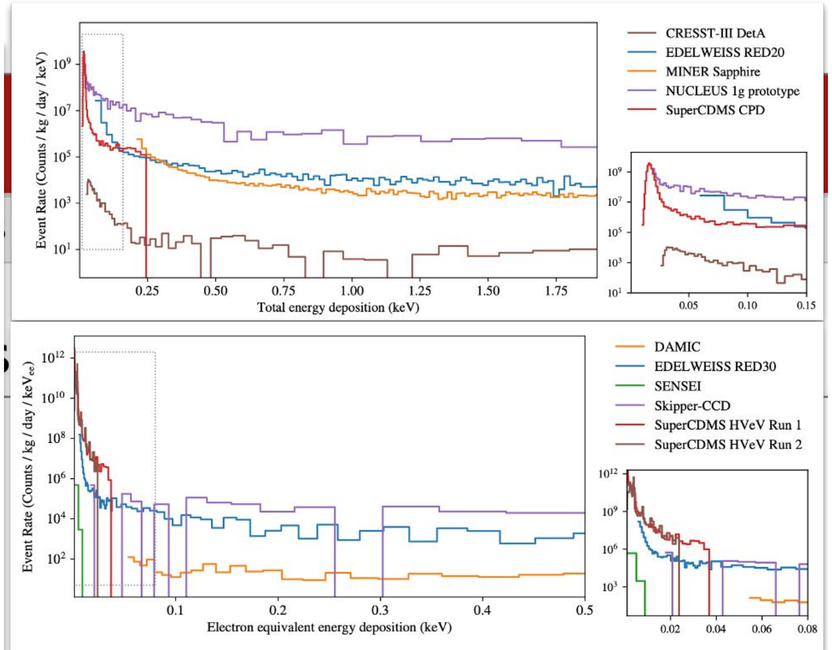
- LZ, Xenon NT, the counting rate is as low as ~ 10 events / ton / year / keV ~ below 10^{-4} events/kg/day, With E > 0.5 keV
- Typical counting rates at lowest threshold semiconductor detectors are large, currently plagued by unexplained excess:

EXCESS

Collaborative summary paper based on the results reported at EXCESS 2021

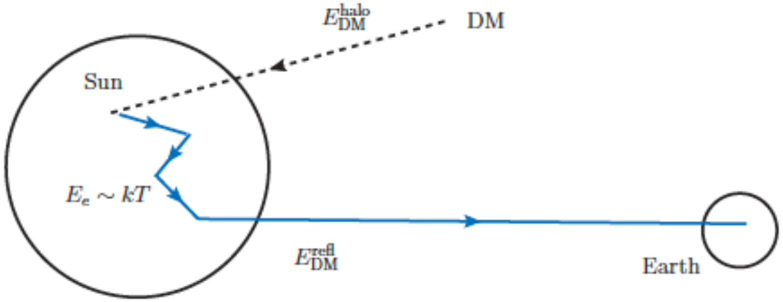
https://arxiv.org/abs/2202.05097

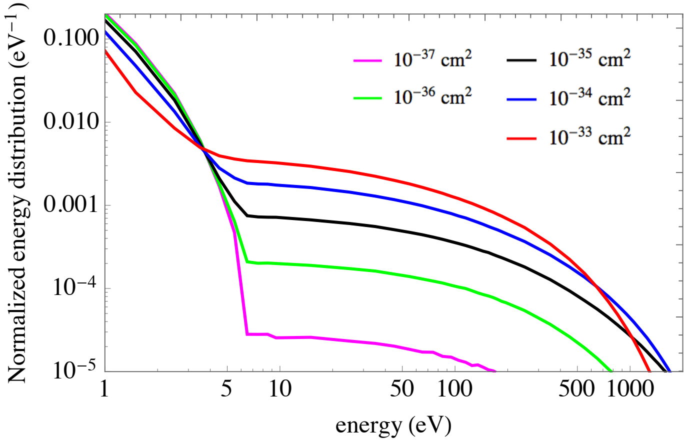
Counting rates in low-threshold semiconductors, at a ~ few 10 eV electron recoil, ~ 10^6 events/kg/day



“Reflected DM”: extending the reach of Xe experiments to WIMP scattering on electrons

- (An, MP, Pradler, Ritz, PRL 2018, An, Nie, MP, Pradler, Ritz, 2108.10332, Emken, 2102.12483, Emken, Essig et al., to appear)
- DM can scatter inside the Sun and get accelerated above the ionization threshold

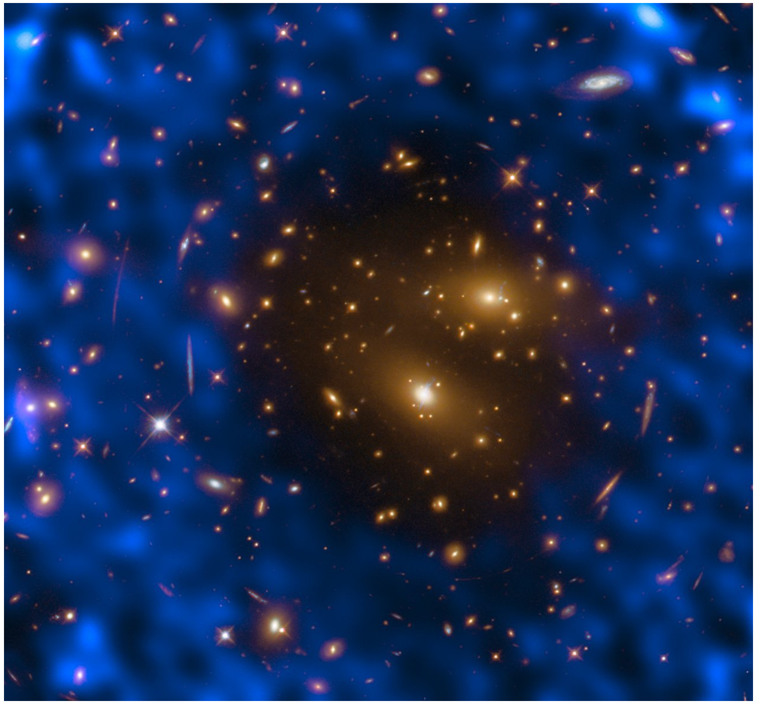




- Initial kinetic energy $m_{dm}(v_{dm})^2/2$ with $v_{dm} \sim 10^{-3}c$ (that has an endpoint at ~600 km/sec)can be changed by scattering with electrons, $v_{el} \sim (2\, T_{core} / m_e)^{1/2}$ ~ up to 0.1 c. In particular $E_{reflected}$ can become larger than $E_{ionization}$.
- Huge penalty in the flux of “reflected” DM ~ 10^{-6} ~ solid angle of the Sun

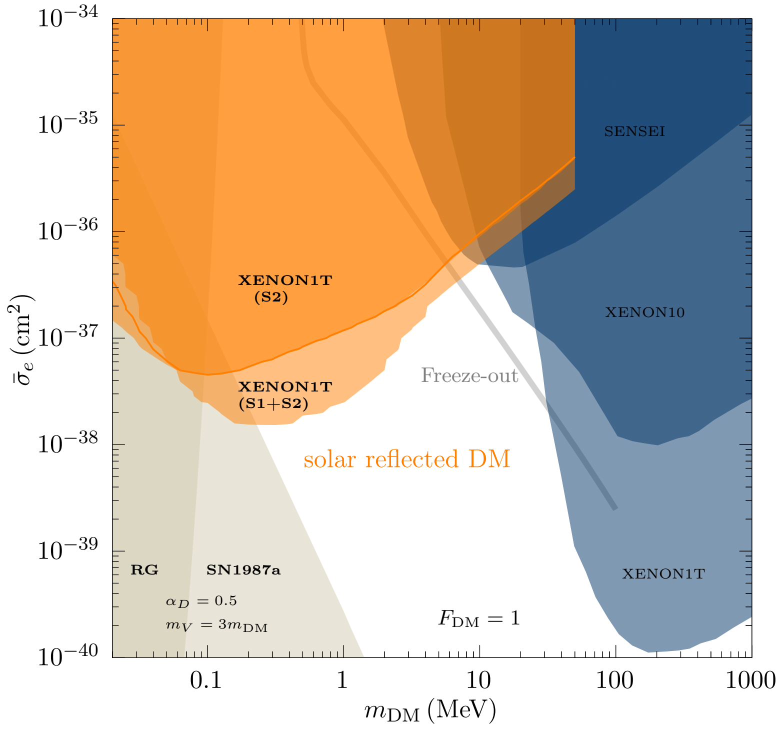
$$\Phi_{\rm refl} \sim \frac{\Phi^{\rm halo}}{4} \times \begin{cases} \frac{4S_g}{3}\left(\frac{R_{\rm core}}{1\,{\rm A.U.}}\right)^2 \sigma_e n_e^{\rm core} R_{\rm core}, & \sigma_e \ll 1\,{\rm pb}, \\ S_g\left(\frac{R_{\rm scatt}}{1\,{\rm A.U.}}\right)^2, & \sigma_e \gg 1\,{\rm pb}. \end{cases}$$

Analogy with Sunyaev-Zeldovich effect

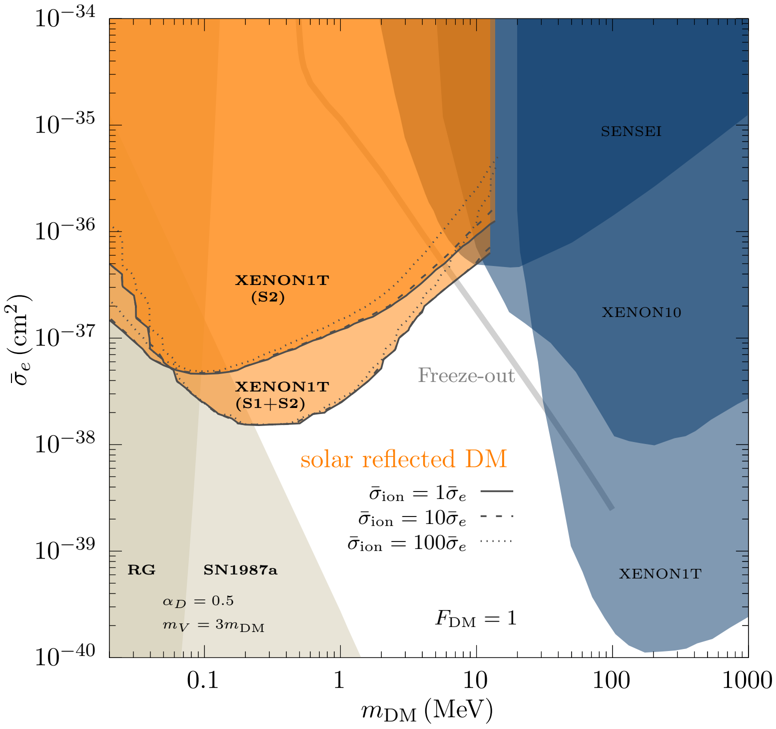


- CMB photons are upscattered by hot gas in clusters of galaxies. Decrement at low frequency and increase at higher frequency.
- Solar electrons will do the same to light dark matter. Sun will be seen as a “hot spot” in dark matter.

Contact mediator, limits on σ_e



only electrons

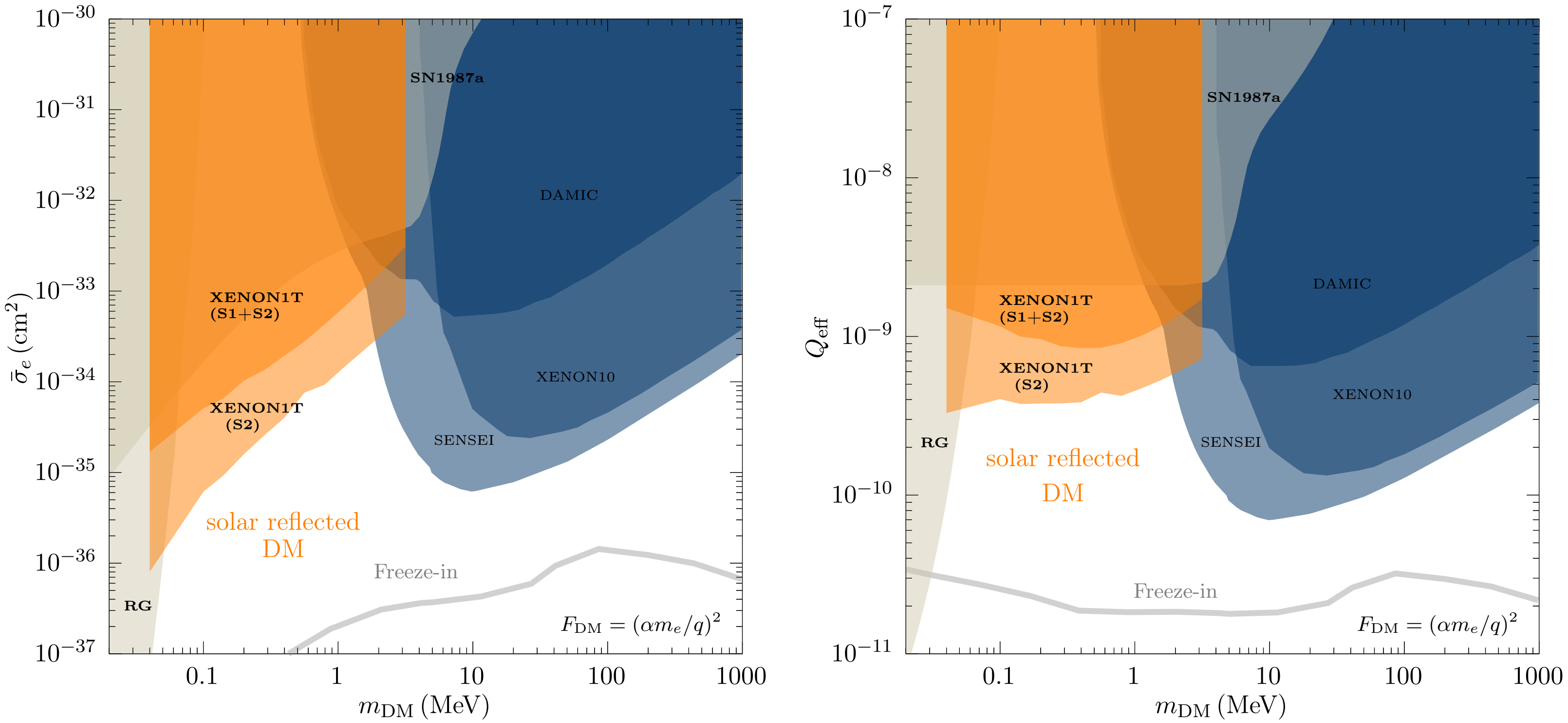


electrons and protons

An, Nie, MP, Pradler, Ritz, 2017, 2022

- Large Xe-based detectors improve sensitivity to σ_e through reflected flux. Sensitivity to cross section on electrons down to 10^{-38} cm^2.
- Significant fraction of "freeze-out" line for DM abundance is excluded in a simple WIMP model.

Massless mediators, limits on σ_e



cross section normalized on $q=m_e\alpha$

Effective charge

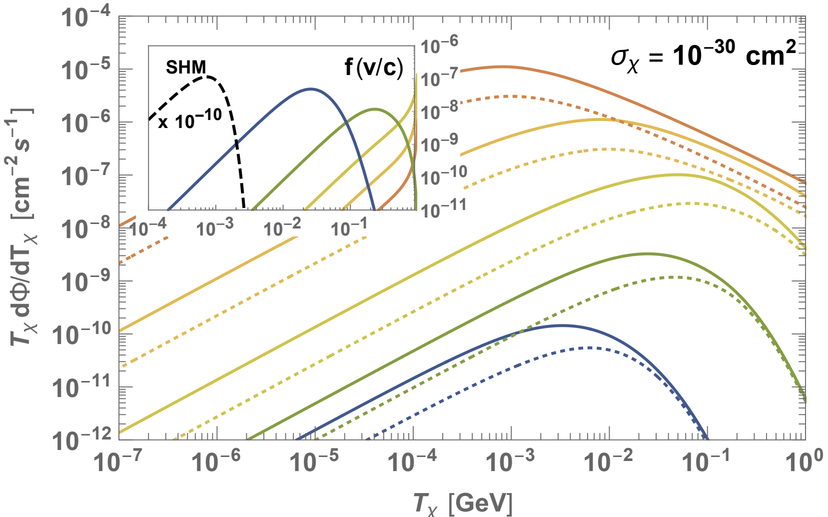
An, Nie, MP, Pradler, Ritz, 2021

- Large Xe-based detectors improve sensitivity to σ_e through reflected flux.
- Second case, massless mediator = milli-charged dark matter, Xe1T is sensitive to $Q_{\rm eff} \sim$ few 10^{-10} e.
- The results are cross-checked with Stony Brook group (some errors corrected)

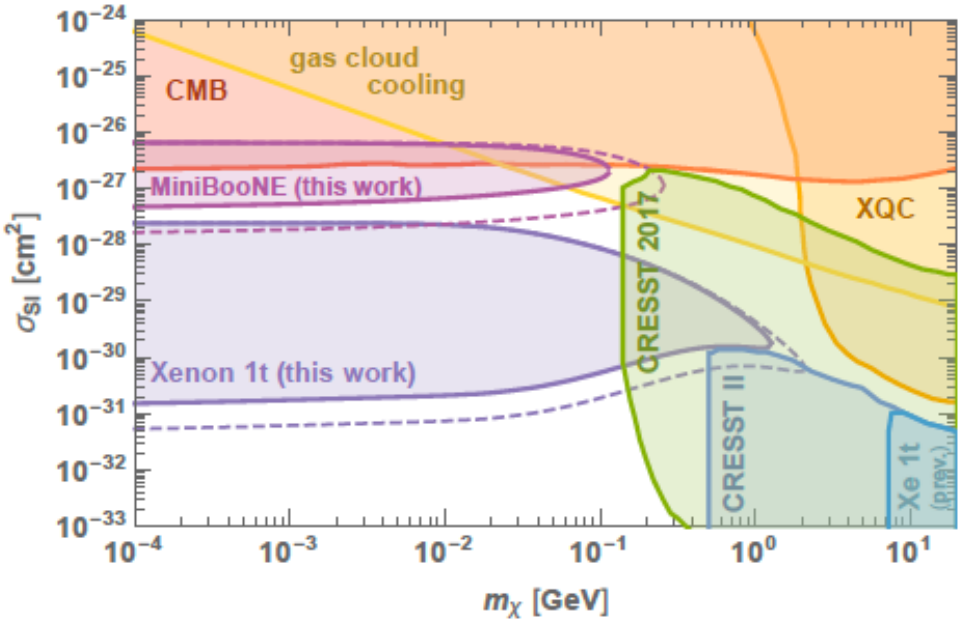
Light DM accelerated by cosmic rays

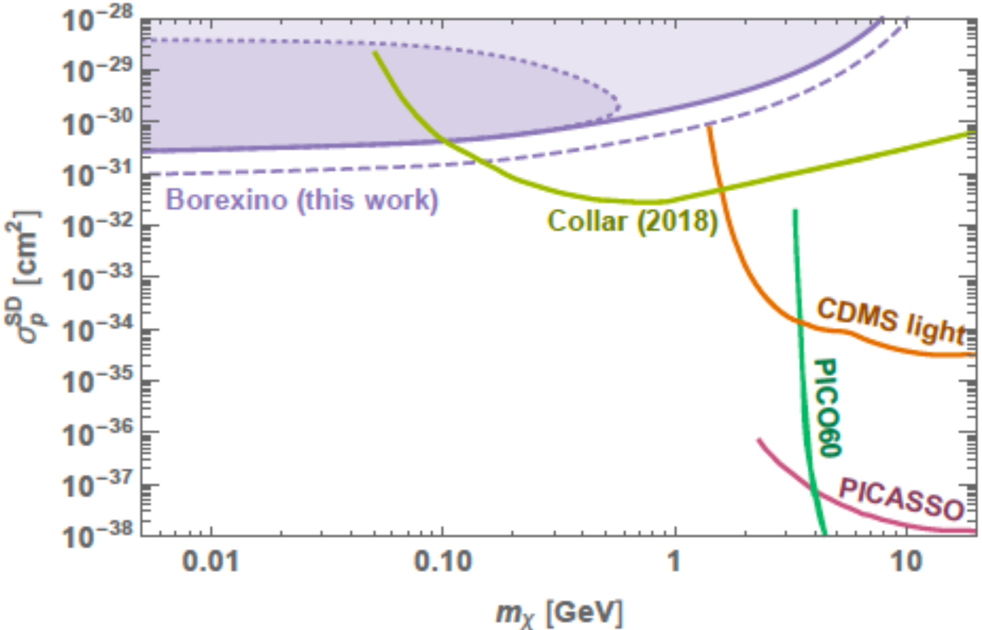
- There is always a small energetic component to DM flux (Bringmann, Pospelov, PRL 2019, others) due to interaction with cosmic rays.
- Typically: MeV DM mass → eV kinetic energy → sub-eV nuclear recoils. No limits for $\sigma_{\text{nucleon-DM}}$ for DM in the MeV range.
- This is not quite true because there is always an energetic component for DM, not bound to the galaxy. Generated through the very same interaction cross section: σ_χ

Main idea: Collisions of DM with cosmic rays generate sub-dominant DM flux with ~ 100 MeV momentum – perfect for direct detection type recoil.



Resulting limits on WIMP-nucleon scattering



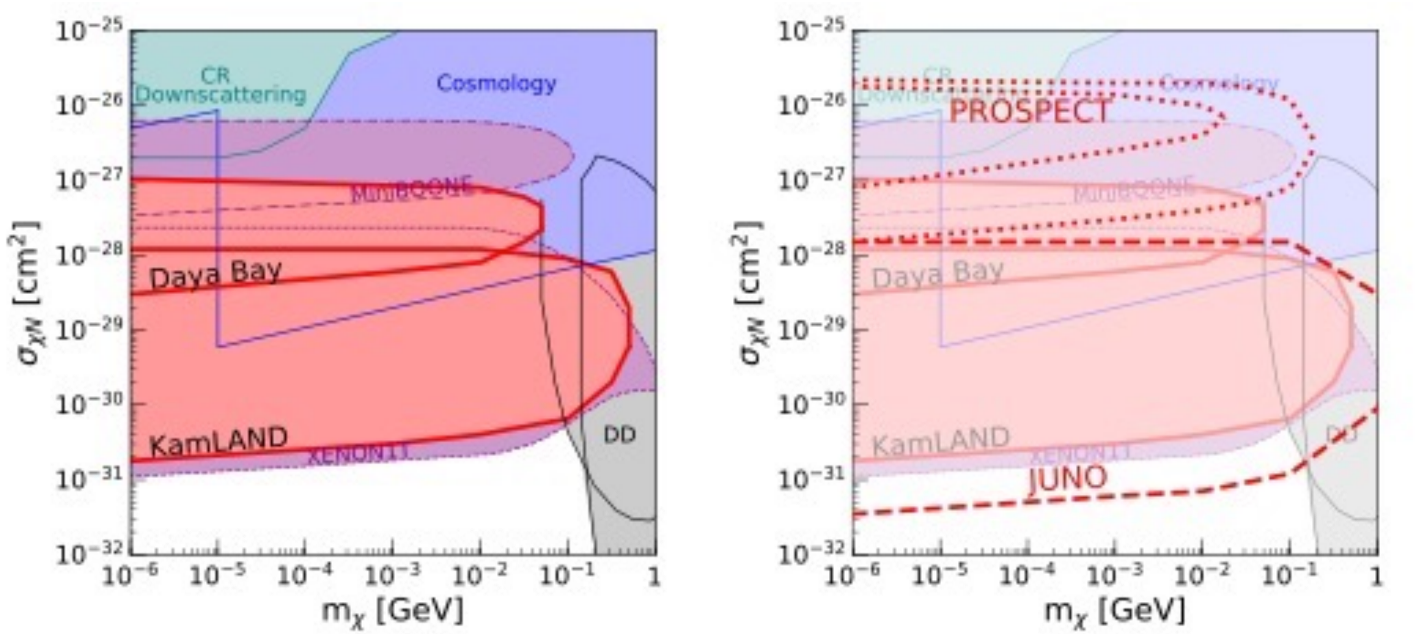


- Spin-independent limits. [Notice the constraint from Miniboone, from measurements of NC nu-p scattering]. Exclusion of $\sigma = 10^{-29}$-10^{-31}cm^2 !

- Scattering on free protons in e.g. Borexino, SNO, SK sre also very constraining e.g. for the spin-dependent scattering.

- (Ema, Sala, Sato had an independent work along the same lines for σ_e)

Updated limits on WIMP-nucleon scattering

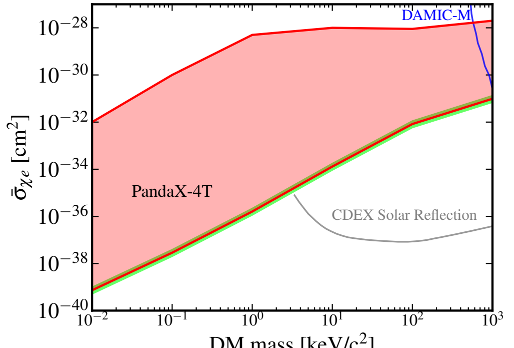


- More neutrino experiments can be used to "fill the gaps", Beacom and Cappiello, 1906.11283
- DM collaborations began to investigate solar & CR reflection idea.

2403.08361

Search for cosmic-ray boosted sub-MeV dark matter-electron scatterings in PandaX-4T

$$\mathcal{L}_{\rm int} = G\bar{\chi}\gamma^{\mu}\chi\bar{e}\gamma_{\mu}e,$$



Two blind areas for direct detection

1. ~MeV scale dark matter: Kin Energy $= mv^2/2 \sim (10^{-3}c)^2(\mathrm{MeV}/c^2) \sim \mathrm{eV}$.

   Below the ionization threshold!

2. Strongly-interacting subdominant component of Dark Matter. Thermalizes before reaching the underground lab,

   Kin energy ~ kT ~0.03 eV

   (Typically cannot be entire DM, but is limited to fraction $f < 10^{-3}$)

   Below the ionization threshold!

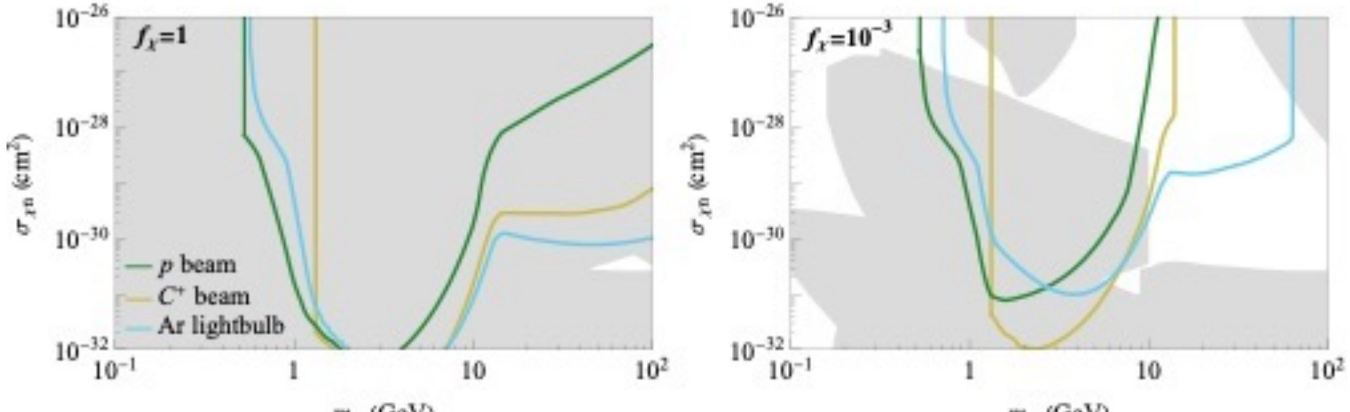
~~Nightmare~~ embarrassing scenario

Rare species of strongly interacting dark matter

- Most advanced direct dark matter detection experiments are so far ahead of other probes that we would not be able to distinguish between ($f_\chi = 1$ and $\sigma = 10^{-47}$ cm^2, and e.g. $f_\chi = 10^{-3}$ and $\sigma = 10^{-44}$ cm^2)

- Assuming a wide range of f_χ , 10^{-10} to 1 is reasonable, as it can be broadly consistent with the freeze-out models.

- If $f_\chi << 1$ (e.g. 10^{-5}) significant blind spots exist for large scattering cross section values (e.g. 10^{-28} cm^2) which can easily arise in models with relatively light mediators. The accumulation and distribution of DM inside astrophysical bodies (most importantly, the Earth) will change.



Model realization

- Dark photon mediate DM with $m_{A'} < m_\chi$.

$$\mathcal{L} = -\frac{1}{4}\left(F'_{\mu\nu}\right)^2 - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2_{A'}\left(A'_\mu\right)^2 + \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi\,,$$

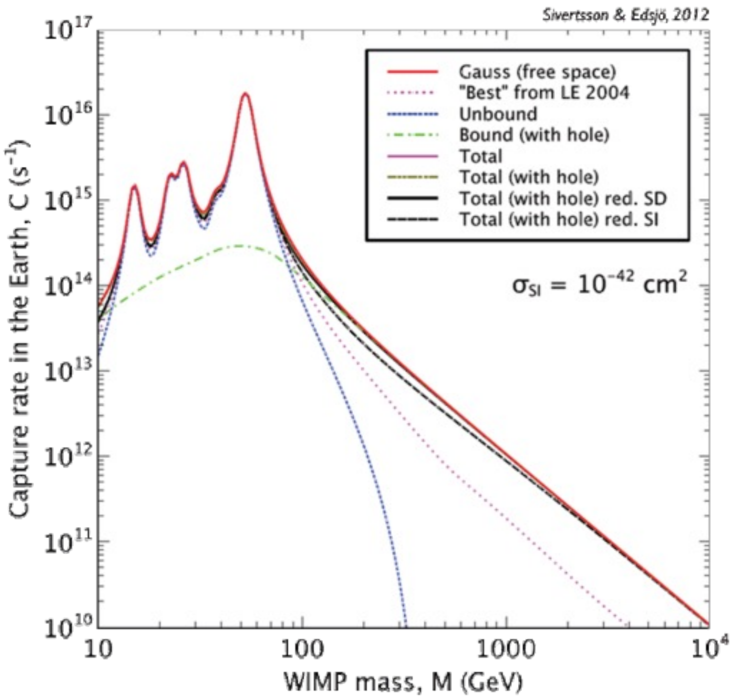
Main process: $\chi\bar{\chi} \rightarrow A'A'$ with $A' \rightarrow$ SM

Dark coupling constant of 0.3 and dark matter mass of 2.5 GeV results in the fractional abundance ~ 3 10^{-9}. Scattering cross section on nucleons is large, if $m_{A'}$ is in 10's of MeV range!

$$\sigma_{\chi A} = \frac{16\pi Z^2\alpha\alpha_d\epsilon^2\mu^2_{\chi A}}{m^4_{A'}}$$

Rare species can be accumulated in large amounts

- When the cross section on nuclei is small, the probability of capture is very small



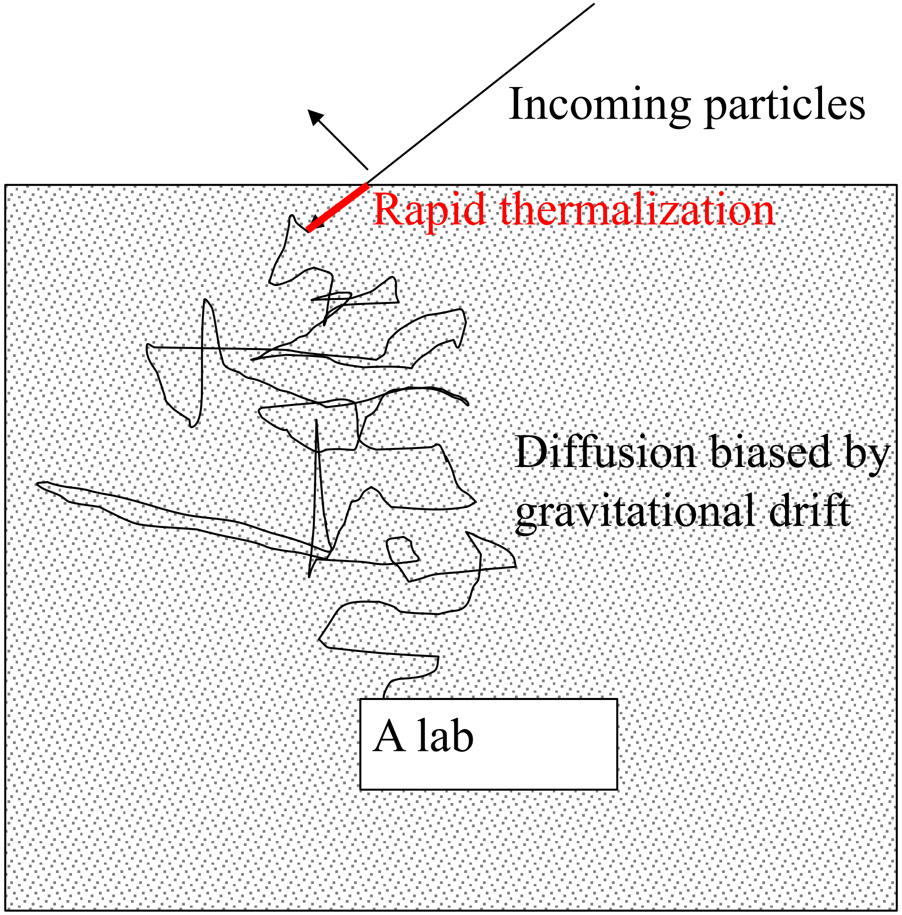
- When the cross section is large, the maximum capture = Flux * $\pi(R_{Earth})^2 \sim 10^{24}$ /sec for a 10 GeV WIMP. More than 10 order of magnitude enhancement.

Dark matter traffic jam

- Rapid thermalization
- Flux conservation: $v_{in} n_{halo} = v_{terminal}\ n_{lab}$.
- Terminal sinking velocity is determined by the effective mobility (~ inverse cross section) and gravitational forcing

$$v_{\rm term} = \frac{3 M_\chi g T}{m_{\rm gas}^2 n \langle \sigma_t v_{\rm th}^3 \rangle}$$

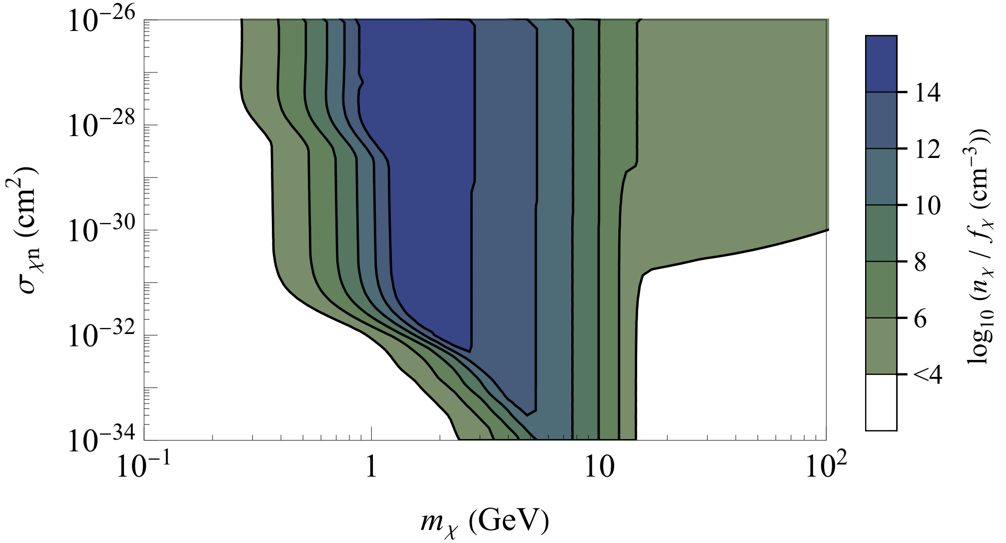
- Change in velocity from incoming ~ 10^7 cm/s to typical sinking velocity of 10 cm/s results in $n_{lab} \sim 10^6\ n_{halo}$. **Not visible to DD**
- At masses < 10 GeV upward flux is important and density goes up.



MP, Rajendran, Ramani 2019 MP, Ramani 2020, Berlin, Liu, MP, Ramani, 2021

Density of trapped particles: best mass range = few GeV.

- Lowest mass – evaporation, Highest mass – traffic jam, intermediate mass – trapping with almost uniform distribution inside Earth's volume.



- Enhancement of the density can be as high as 10^{14}. (First noted by Farrar and collaborators)
- "Less is more". Having 1 GeV particle with $f_\chi = 10^{-5}$ fractional DM abundance may result in ~ $10^9/\mathrm{cm}^3$ concentrations, not $10^{-5}/\mathrm{cm}^3$. This has to be exploited.

Signature #1: annihilation inside the SK volume

- DM is often searched by its annihilation to neutrinos, with subsequent conversion of neutrinos to visible energy inside neutrino telescopes
- We propose that DM can be searched with direct annihilation inside detector volumes in the mass range ~ 1-5 GeV.

- Hydrostatic population is built up by incoming DM until it is counter-balanced by the annihilation (we assume s-wave). The distribution over radius is given by Euler eq. (see our papers, + Leane, Smirnov)

$$\frac{\nabla n_\chi(r)}{n_\chi(r)} + (\kappa + 1)\,\frac{\nabla T(r)}{T(r)} + \frac{m_\chi g(r)}{k_B T(r)} = 0$$

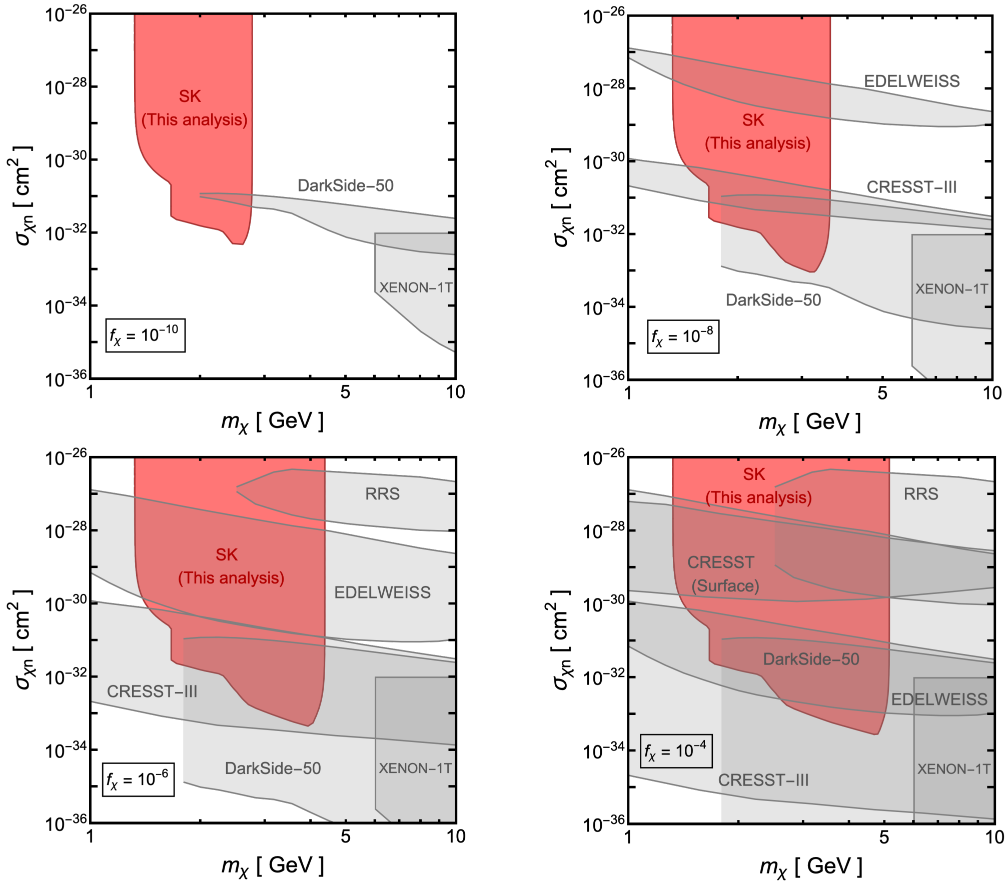
- Annihilation rate inside SK is easily calculable

$$\Gamma^{\rm SK}_{\rm ann} = \langle \sigma v \rangle_{\rm ann} n_\chi^2(R_\oplus) V_{\rm SK}$$

$$\Gamma^{\rm SK}_{\rm ann} = \Gamma_{\rm cap} \times \frac{V_{\rm SK} G_\chi^2(R_\oplus)}{4\pi \int_0^{R_\oplus} r^2 dr G_\chi^2(r)} \xrightarrow{G_\chi \to 1} \Gamma_{\rm cap} \times \frac{V_{\rm SK}}{V_\oplus},$$

Similar to di-nucleon decay signatures

- Constraints from a possible background-free search
- Lower masses evaporate, heavier masses sink too much.

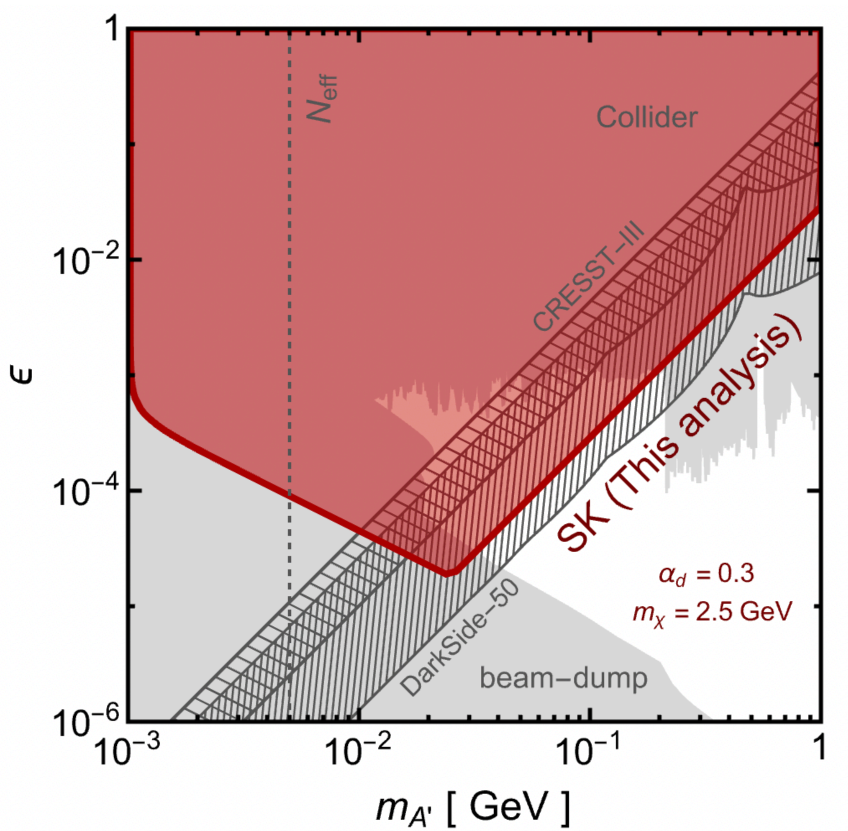


Assuming a background free search with $2m_\chi$ invariant mass energy release. In many models: strong similarity to nn→$\pi^0\pi^0$ search by SK (background free, ~0.1 signal efficiency).

Constraints on dark photon mediated DM

- Dark photon mediate DM with $m_{A'} < m_\chi$.

$$\mathcal{L} = -\frac{1}{4}\left(F'_{\mu\nu}\right)^2 - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2_{A'}\left(A'_\mu\right)^2 + \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi\,,$$



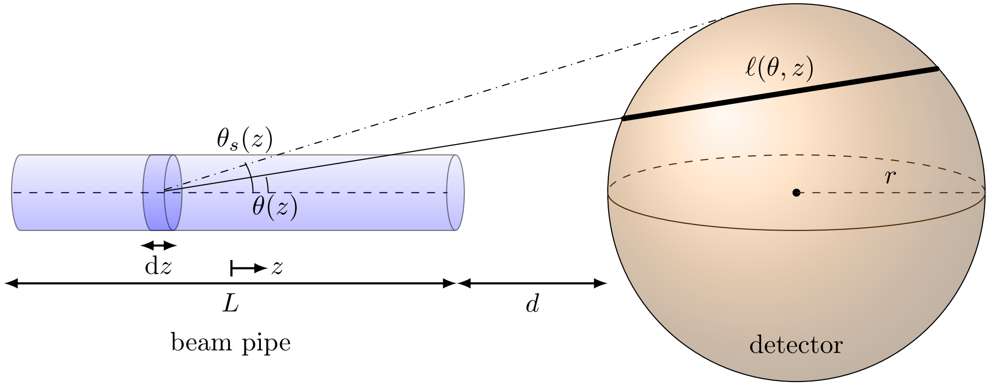
$$\chi\bar{\chi} \to A'A' \text{ with } A' \to \text{SM}$$

Dark coupling constant of 0.3 and dark matter mass of 2.5 GeV results in the fractional abundance ~ 3 10^{-9}. New parameter space covered.

For heavier than 5 GeV masses main signature are neutrinos from Earth's center.

Signature # 2: Using underground accelerators to "accelerate" dark matter

- Some of the underground Labs that host Dark Matter detectors, also have nuclear accelerators (LUNA, JUNA) for a completely different purpose: studies of nuclear reactions.
- We propose to couple nuclear accelerators and dark matter detectors: accelerated protons (or other nuclei) can strike DM particles that can subsequently be detected with a nearby detector.
- $\chi + p \rightarrow \chi_E + p$



$Z + \chi \rightarrow Z_E + \chi$

- This is going to be relevant for models with large DM-nuclear cross section where A. interaction is enhanced, B. density is enhanced.

Spectrum of recoil

- Energy of nuclei in the detector after experiencing collision with the accelerated DM.

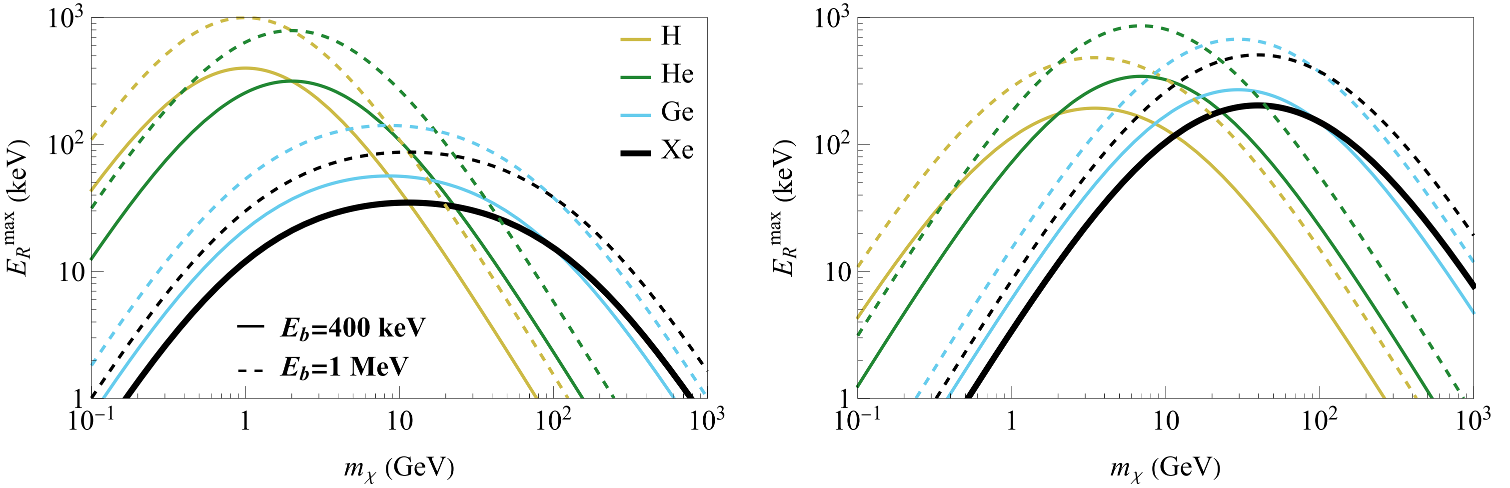


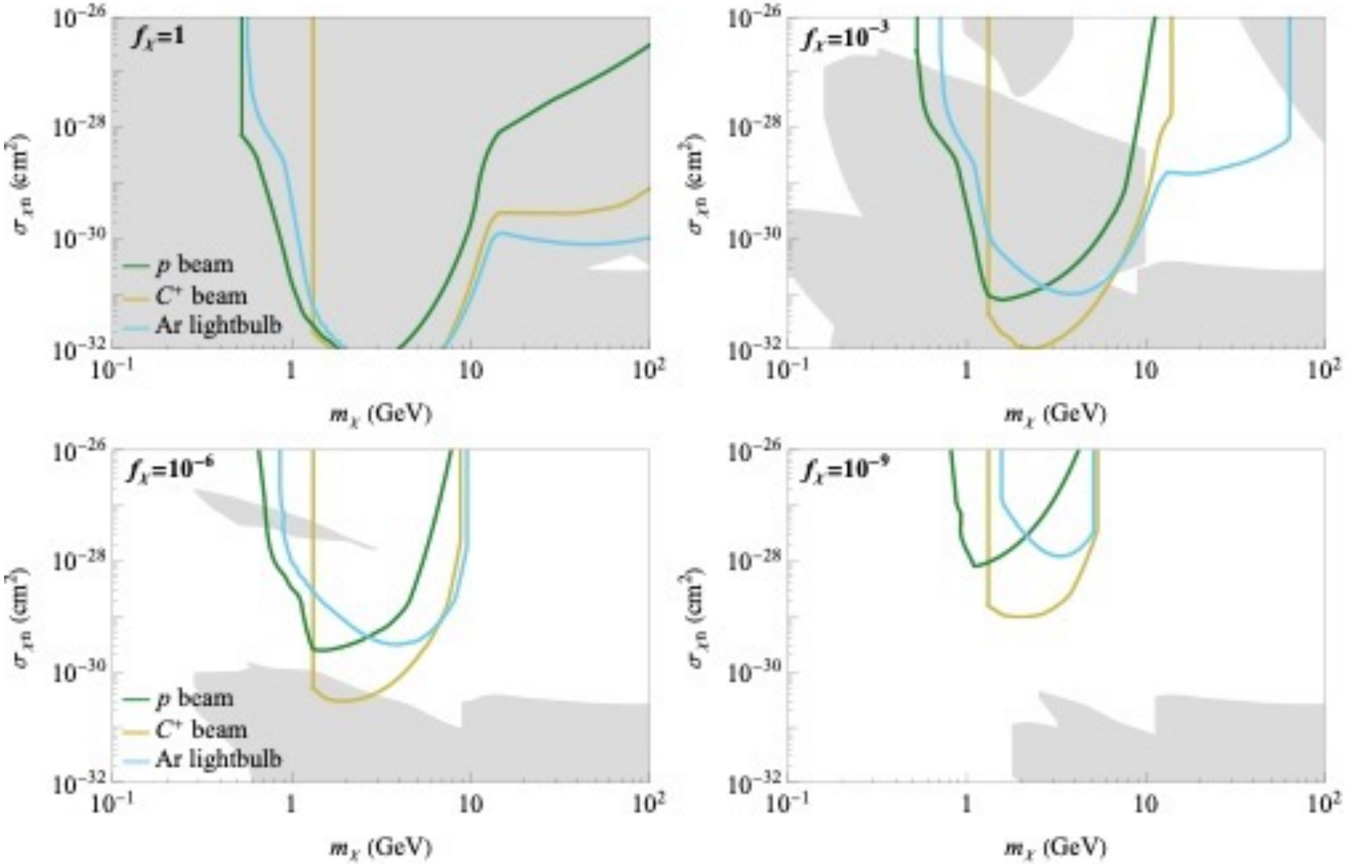
FIG. 3. Maximum nuclear target recoil energies $E_R^{\max}$ for dark matter upscattered by beams of protons (left) or carbon (right) with kinetic energies $E_b = 0.4$ MeV (solid) and $E_b = 1.0$ MeV (dashed) for a selection of target nuclei.

Energy of accelerator is ~ MeV, and given that the thresholds in many detectors are keV and lower, this detection scheme is realistic.

- See details in M. Moore et al, 2022.

Possible new reach in the parameter space

- While 100% fraction of these DM particles is excluded by combination of ballon + underground experiments (gray area), the accelerator+detector scheme is sensitive to small f_χ.



- This is a promising scheme that can be tried without additional enormous investment, with existing accelerators (LUNA, JUNA)

Signature #3: Nuclear reactors as beam dumps

- Commercial reactors produce over 10^{20} neutrons/sec. It is a source of anti-neutrinos, and can also be viewed as a neutron beam dump.

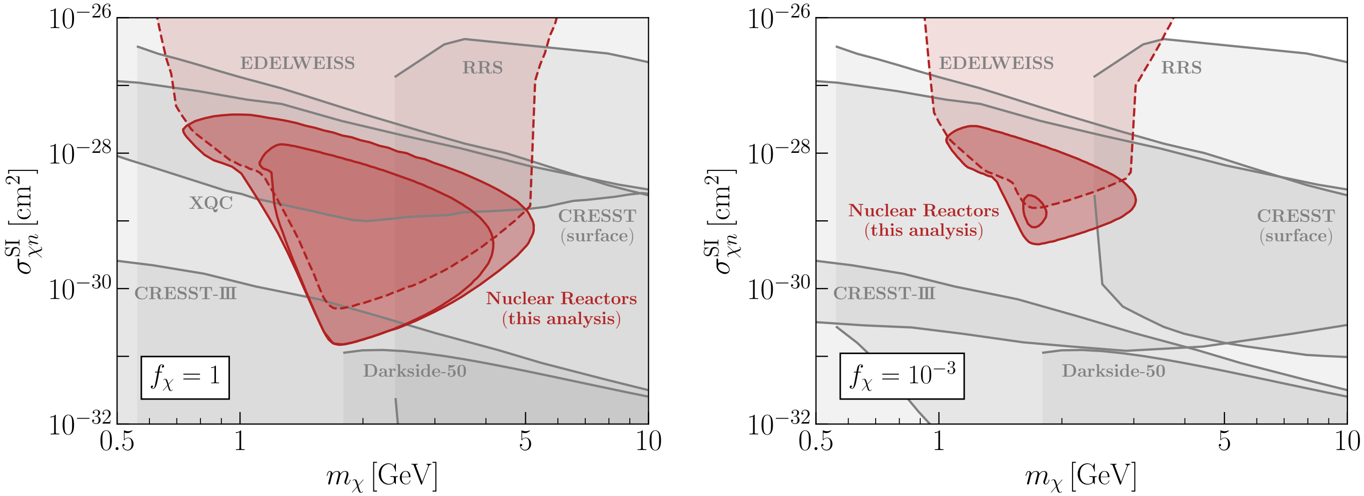
- Recently (last O(5) years), there has been explosion of efforts to detect coherent nucleus-neutrino scattering (CEνNs): i.e. direct detection style detectors are brought to O(20-30m) proximity to reactor cores. Importantly, these detectors are achieving low counting rates (e.g. CONUS collaboration).

- If there is a "bath" of thermalized DM particles, fast neutron scattering will create velocitized DM, $\chi + n \rightarrow \chi_E + n$.

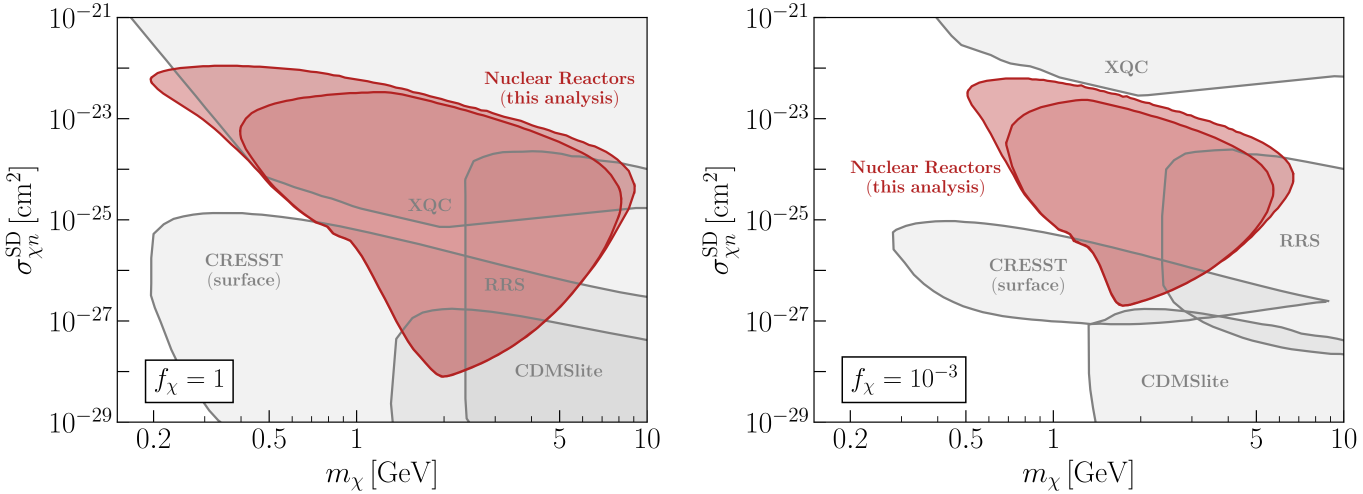
- Ema, MP, Ray, 2024, reanalyzed the results of the CEνNs searches using CONUS experiment, and translated it to constraints on GeV dark matter.

Constraints on upscattering of DM

Spin-independent scattering



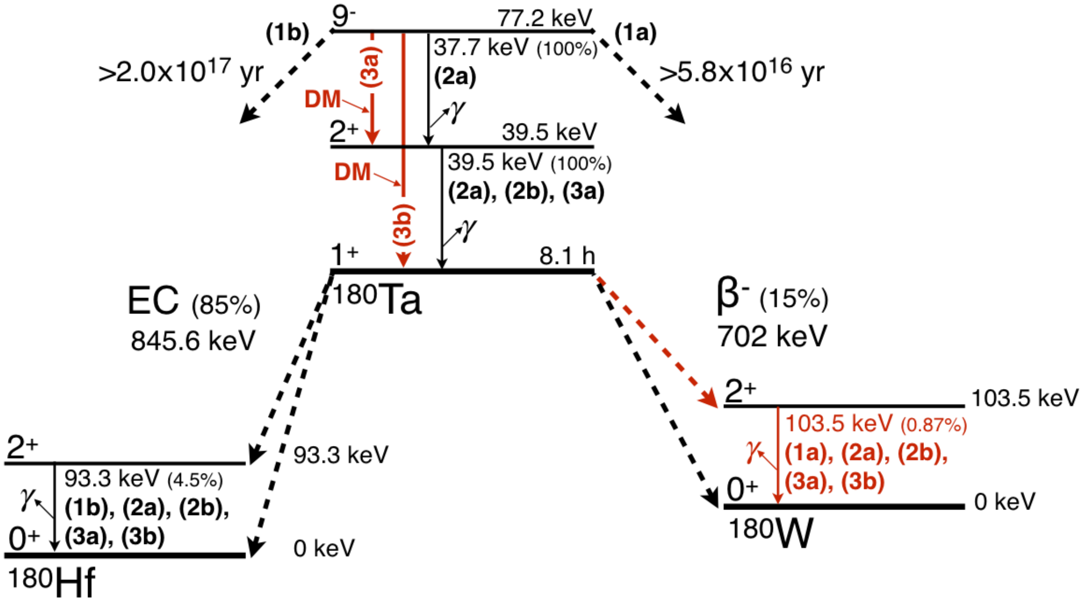
Spin-dependent scattering



Novel limits are derived for spin-dependent scattering. No new limits for spin-independent case, as large amount of shielding (over 6m of concrete) leads to suppression of DM energy at CONUS detector location. *Motivates experiments at research reactors with less shielding.*

Signature # 4: DM-catalyzed quenching of nuclear isomers

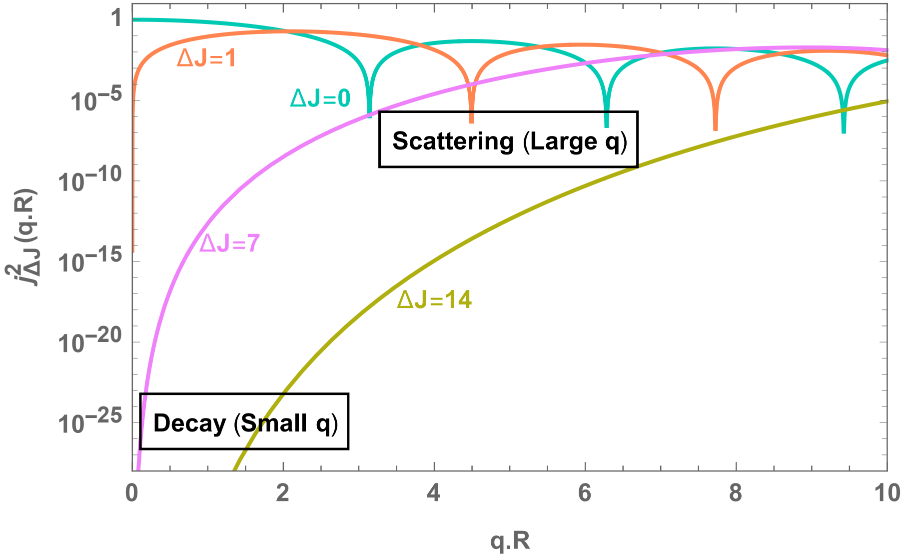
Tantalum180m level structure



- Lifetime of the 9- level exceeds 10^{17} years (not established yet)
- Natural abundance is not all that small, 0.01%.

DM is a source of large recoil momentum → Enhancement of decay

- Momentum transfer k mediated in the γ,β transitions is small: on the order of decaying energy, e.g. 100 keV.
- $(R_{nuclear}\ k) \sim 10^{-3}$. Enters in the HUGE power in the rate, $(R_{nuclear}\ k)^{2\Delta L} \sim (10^{-3})^{14}$.
- Dark matter is rare etc etc – but it carries large k! $k \sim / R_{nuclear}$ easily. Kinematic suppression by $(R_{nuclear} / \lambda)^{2\Delta L}$ is gone.



$$k_{DM} \sim (2\ \Delta E\ \mu_{N\chi})^{1/2} \sim$$

$$(2\ \Delta E\ 100\ \text{GeV})^{1/2} = 120\ \text{MeV}$$

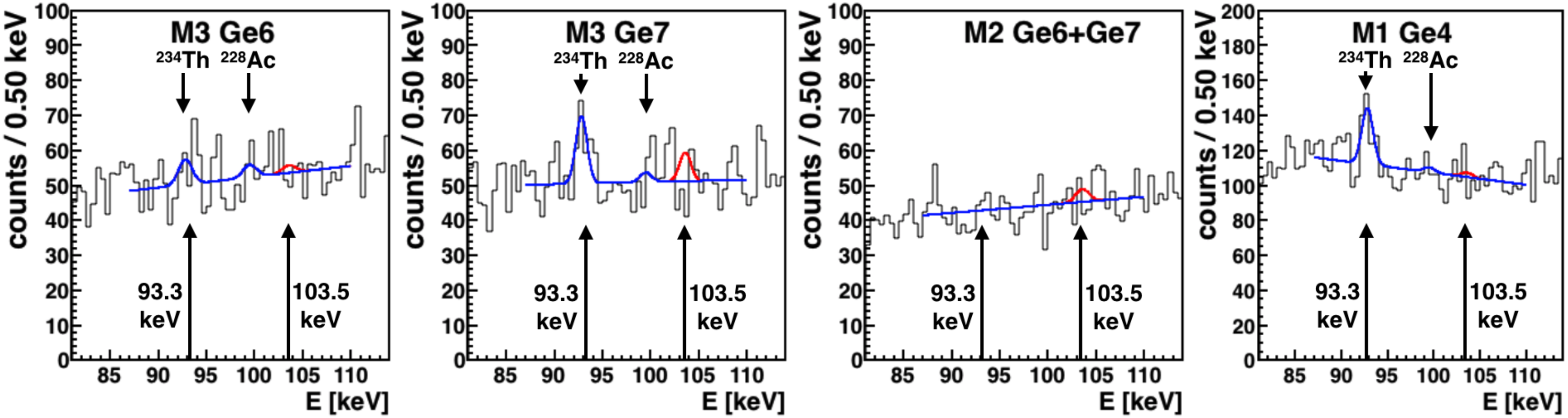
Interesting candidate isomers

Isomer	$\Delta E_N^{\max}$	levels	Half-life	Source	Amount	Signal	Hindrance (F_γ)
^{180m}Ta	77 keV	2	$> 10^{16}$ y	Natural	0.3 gram year	Ground State Decay / Secondary	0.16[14]
^{137m}Ba	661 keV	2	2.55 min	Nuclear Waste	0.5 gram year	Secondary	1
^{177m}Lu	970 keV	27	160 d	Medical Waste	1 mg year	Secondary	0.17[a]
^{178m}Hf	2.4 MeV	110	31 y	Old experiments	1 μg year	γ end-point / Secondary	0.29[a]

[a] Hindrance factors for Lu and Hf derived from the observed half-lifes.

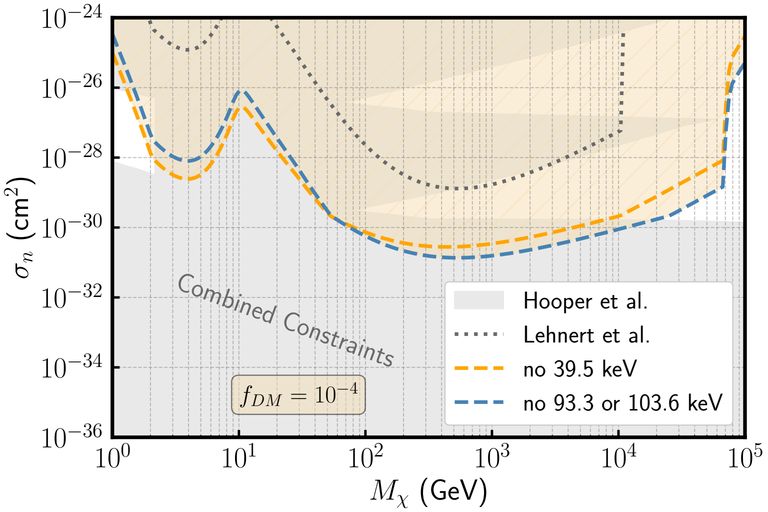
- Tantalum 180m is naturally occurring. Non-radioactive. Provides the safest opportunity.
- First searches have been performed, but there is a sustained interest to this element from the nuclear physics community.

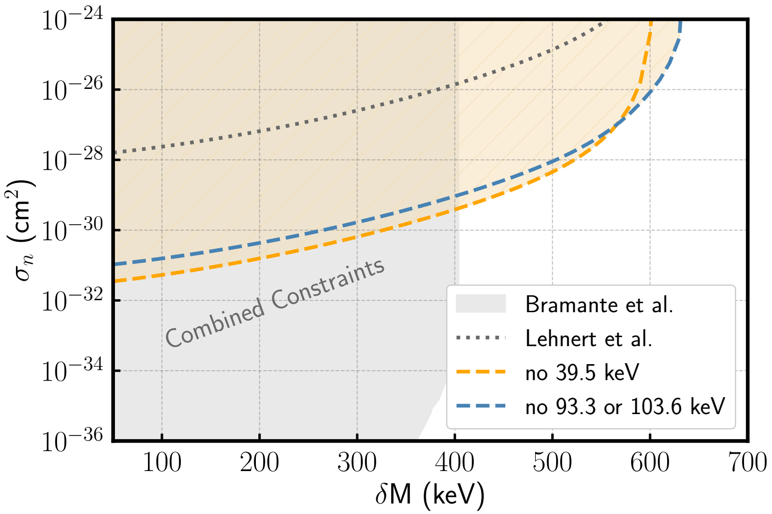
Experimental search



- DM induces de-excitation of Ta180m down to the ground state.
- Ta180gs decays within a few hours to W and Hf. These decays produce 103.5 and 93.3 keV gammas.
- Search of these gammas above the background in the old data from HADES lab produced upper limits on DM-induced de-excitation of Ta180m. $T_{1/2}>1.3\ 10^{14}$ yr

Experimental constraints





- Left: constraints on strongly-interacting DM, that constitutes a 10^{-4} fraction of the total DM abundance. New parameters relative to XQC are covered.
- Right: constraints on inelastic dark matter. New mass splittings are covered.
- Bulk Ta can be used to “accelerate” DM.
- New experimental study by Majorana: 2306.01965

Conclusions

- *There are important "difficult corners" in direct detection. For light dark matter below few MeV best limits come from Xenon+ solar DM.*
- Interesting physics can result from *rare species of DM*, as their elastic cross sections can be very sizeable resulting in enhanced population inside the Earth (traffic jam and hydrostatic population).
- The diversity of DM models creates a diversity of experimental signatures – now it is the right time to explore them, as much investment is made into direct detection of dark matter.
- Signature 1: direct annihilation inside the neutrino detectors (strong constraints from SK).
- Signature 2: nuclear accelerators to up-scatter DM and detect recoil.
- Signature 3: DM experiments at nuclear reactors can be used.
- Signature 4: nuclear isomer de-excitation is catalyzed. Ta180 is a very attractive candidate. No decay (or DM-induced de-excitation) detected thus far.